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Peak effect and its evolution with defect structure in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films at microwave frequencies

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The vortex dynamics in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films have been studied at microwave frequencies. A pronounced peak in the surface resistance R_s is observed in these films at frequencies of 4.88 and 9.55 GHz for magnetic fields varying from 0.2 to 0.8 T. The occurrence of the peak in R_s is crucially dependent on the depinning frequency ω_p and on the nature and concentration of growth defects present in these films. Introduction of artificial defects by swift heavy ion irradiation with a 200 MeV Ag ion at a fluence of 4×10^{10} ions/cm² enhances ω_p and suppresses the peak at 4.88 GHz but the peak at 9.55 GHz remains unaffected. The peak can be associated with a transformation of the flux line lattice (FLL) from a pinned solid to a depinned liquid in a depinning frequency domain similar to the order-disorder transformation of the FLL associated with the peak effect in critical currents in dc or low frequencies as the temperature or field is increased. A second peak at lower temperature has also been observed at 9.55 GHz. This could be related to twin boundaries from angular dependence studies of R_s . Based on the temperature variation of R_s , vortex phase diagrams have been constructed at 9.55 GHz.

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I. INTRODUCTION

The dynamics of vortices forming the flux line lattice (FLL) in the mixed state of type II superconductors has been a subject of great interest over the last few years.¹⁻³ The competition between intervortex interactions and pinning by disorder or defects⁴⁻⁶ gives rise to the widely studied peak effect (PE) phenomenon which is the occurrence of a peak in the critical current density J_c below its superconducting-normal phase boundary. The earliest understanding of this phenomenon involves the rapid softening of the elastic moduli of the FLL as $H_{c2}(T)$ is approached which allows pinning sites to distort the lattice more strongly, leading to a sharp rise in the critical current density.⁷⁻⁹ This is described in the Larkin-Ovchinnikov collective pinning model as a reduction in the correlation volume V_c which is the characteristic size over which the FLL is ordered and where the effective pinning force on the FLL is given by

$$BJ_c(H) = (n_p \langle f^2 \rangle / V_c)^{1/2}, \quad (1)$$

where n_p is the density of pinning sites, f is the elementary pinning force parameter, B is the magnetic induction, and V_c is the volume of Larkin domain. This scenario is generally true for weak collective pinning (point defects and uncorrelated defects) where $n_p \gg n_v$ (n_v is the vortex density). On the other hand, there is increasing evidence that for strong dilute pinning (e.g., twin planes in twinned crystals) where $n_p < n_v$, the transition to disorder above the peak temperature T_p , is more likely to be accompanied by a plastic motion of the vortex lattice.

Up to now, the statics and dynamics of the FLL have been probed at low frequencies by measurements of the dc critical current density J_c and by measurement of surface impedance in the radiowave or microwave regime. At high frequencies

(low currents) the vortices undergo reversible oscillations and even a small microwave current leads to enhanced dissipation as frequency ω approaches the depinning frequency ω_p which would otherwise have occurred at high dc transport currents or at high magnetic fields. The directly accessible quantity in the microwave regime is the surface impedance given by $Z_s = R_s + iX_s$, where the surface resistance R_s determines dissipation and yields information about the vortex dynamics and surface reactance X_s is a measure of the complex penetration depth in a magnetic field, at $T < T_c$.¹⁰

The earliest theoretical model for the dynamics of the Lorentz force of alternating screening currents at high frequencies was given by Gittleman and Rosenblum¹¹ and thereafter refined considerably.¹² We use the Gittleman and Rosenblum model not only because of its simplicity but also because of the fact that at frequencies > 1 GHz (such as those used in our measurements), the vortices are less sensitive to flux creep in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin films as demonstrated by Revenaz *et al.*¹⁰ and reiterated by Golosovskiy *et al.*¹⁰ Therefore, for vortices oscillating close to the minimum of the pinning potential and experiencing a restoring force κ_p (determined by the curvature of the pinning potential), the equation of motion for a massless flux line, neglecting Hall and stochastic thermal force, is given as

$$\eta \dot{x} + \kappa_p x = J \times \phi_0, \quad (2)$$

where $J(t)$ is the microwave driving current, x is the displacement from equilibrium, $\eta = \phi_0 H_{c2} / \rho_n$ is the Bardeen-Stephen viscous drag coefficient, and ρ_n is the normal state resistivity. The vortex impedance is thus given by

$$\rho_v = \frac{\phi_0 B}{\eta} \frac{1}{(1 + i\omega_p/\omega)} = \frac{\omega^2 - i\omega\omega_p}{\omega^2 + \omega_p^2} \frac{H}{H_{c2}} \rho_n. \quad (3)$$

R_s is thus given as¹³

$$R_s = \left(\frac{H}{H_{c2}} \rho_n \right)^{1/2} \left[\frac{\mu_0 \omega^2}{\sqrt{\omega^2 + \omega_p^2}} \left(\frac{\omega_p}{2\sqrt{\omega^2 + \omega_p^2}} + 1 \right) \right]^{1/2}. \quad (4)$$

The characteristic depinning frequency $\omega_p = \kappa_p / \eta$ separates the low-frequency regime ($\omega < \omega_p$) dominated by pinning with inductive response, from a high-frequency regime ($\omega > \omega_p$) of free vortex flow with dissipation. From the above expression, we see that for $\omega \ll \omega_p$, $R_s = C \sqrt{\omega^2 / \omega_p}$, whereas for $\omega \gg \omega_p$, $R_s = D \sqrt{\omega}$, where C and D are constants.

Although there have been few studies of the vortex dynamics at microwave and radio frequencies there are no reports on the observation of PE at microwave or radio frequency in either low- T_c or high- T_c superconductors. However, recently we have reported¹⁴ an observation of PE in $\text{DyBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (DBCO) thin films at a frequency of 9.55 GHz. We had proposed a model dependence of ω_p on temperature T , whereby κ_p (or ω_p) has a similar temperature and field variation as J_c and shows a peak near $T_c(H_{c2})$ which in turn reflects as a minimum in R_s .

Pinning of the FLL due to material disorder (growth defects as dislocations, stacking faults, point and surface defects) plays an important role in the transport properties of type-II superconductors. Ion irradiation is a well-established method to increase the lattice defect concentration in a controlled way with homogenous spatial distribution over the sample area.¹⁵ Whereas point defects are not so effective pinning centers because of their extremely small coherence length, cylindrical defects of radius equal to the coherence length act as strong pinning centers. The strong pinning provided by such columnar defects (CD's) completely alters the equilibrium properties of a clean vortex state.¹⁶ In this work, we show that the peak in R_s of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin films at 4.88 GHz caused by random uncorrelated defects is suppressed with the introduction of artificial correlated columnar defects by 200 MeV Ag ion irradiation while the peak at 9.55 GHz remains unaffected.

II. EXPERIMENTAL

For the present study, several c -axis oriented YBCO ($T_c = 92 \pm 0.2$ K, measured with ac susceptometer and four probe resistivity techniques) thin films (thickness 2500 Å), were grown by the pulsed laser deposition (PLD) technique on single crystal $\langle 100 \rangle$ LaAlO_3 substrates. For microwave transmission studies, the films were patterned into linear microstrip resonators of width 175 μm and length 9 mm using UV photolithographic techniques. Details of the microwave measurements and determination of R_s have been described earlier.¹⁷ dc magnetic field varying from 0.2 up to 0.8 T was applied perpendicular to the film plane (parallel to the c axis of the film) using a conventional electromagnet. Since the high frequency penetration depth λ of YBCO thin films measured earlier¹⁷ is in the range 1500–2500 Å for the temperature range 0–77 K, a major fraction of the YBCO microstrip resonator is driven into the mixed state at the microwave

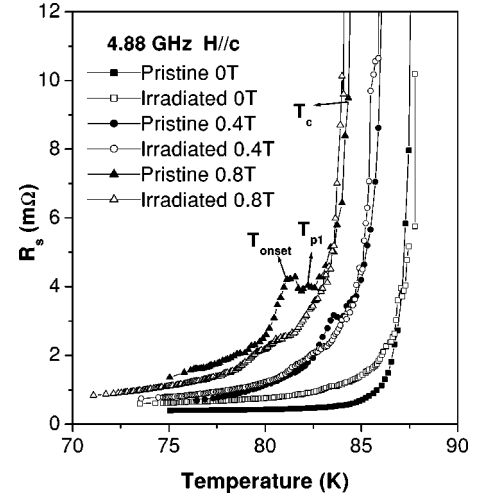


FIG. 1. R_s vs T plots at 4.88 GHz for various applied fields (H/c) for both pristine and irradiated films, at 10 dBm microwave power.

frequencies. The temperature instability during measurements was always < 30 mK. Irradiation was carried out using the 15 UD Pelletron accelerator at Nuclear Science Center, New Delhi using 200 MeV $^{109}\text{Ag}^{+14}$ ions at a fluence of 4×10^{10} ions/cm² (corresponding to a matching field $B_\phi \sim 0.8$ T). For this choice of ion species and energy (electronic energy loss = 2.3 keV/Å) CD's are created.¹⁸

III. RESULTS AND DISCUSSION

The variation of R_s with temperature, before and after irradiation, at various magnetic fields at 4.88 GHz (corresponding to the fundamental excitation of the microstrip) is shown in Fig. 1. At field values > 0 T, R_s is found to exhibit a peak followed by a sudden dip before T_c . Irradiation with 200 MeV Ag ions at a fluence of 4×10^{10} ions/cm² causes the peaks to be suppressed. Figure 2 shows the temperature variation of R_s at 9.55 GHz (first harmonic excitation of the microstrip). Here we observe an additional peak at lower temperatures for fields > 0 T. However, there is no suppression of peaks with 200 MeV Ag irradiation. A manifestation of irradiation induced disorder is reflected in an increase in R_s at field values up to the matching field of 0.8 T. At the matching field of 0.8 T, the effect of pinning by CD's far surpasses the effect of disorder introduced by irradiation and a drop in the R_s values is observed.

The plots shown in Figs. 1 and 2 were obtained at 10 dBm microwave power level. However, R_s measurements were also carried out at lower power levels of 0, 2, and 5 dBm which did not show a shift in the position of the peaks both at 4.88 and 9.55 GHz. This observation indicates that our measurements are in the linear regime with microwave currents lower than the low frequency J_c (zero field transport J_c measured in these films using microbridge is $\sim 2 \times 10^6$ A cm⁻² at 77 K). We had also performed isothermal magnetization versus field (M - H) measurements in the field range 0–3 T in YBCO thin films grown simultaneously with the microstrip resonator samples. None of these measure-

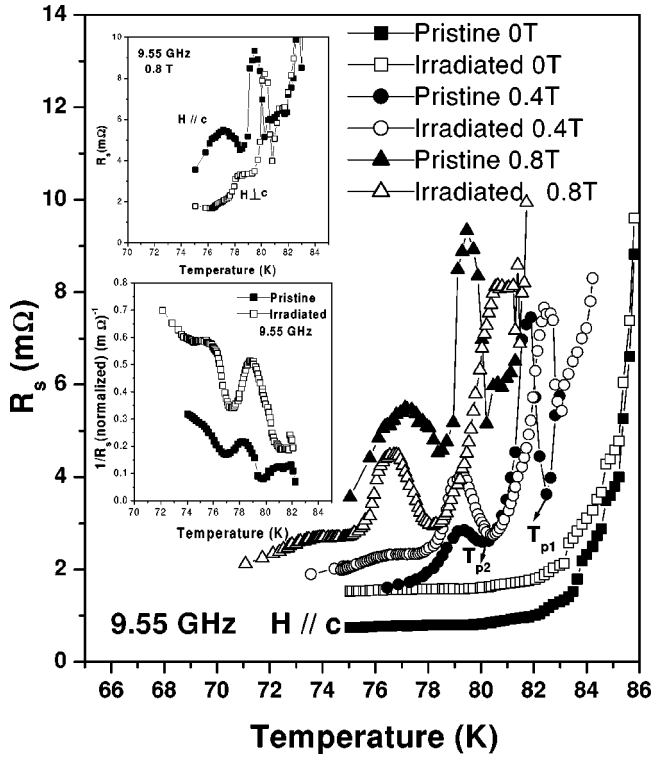


FIG. 2. R_s vs T plots at 9.55 GHz for various applied fields ($//c$) for both pristine and irradiated films at 10 dBm microwave power. The top inset shows the R_s vs T plot at 0.8 T for $H//c$ and $H\perp c$ at 9.55 GHz. The bottom inset shows $1/R_s$ (normalized) vs T plots at 0.4 T for $H//c$ at 9.55 GHz.

ments showed a peak effect. One of the differences between the magnetization and microwave measurements on YBCO thin films is that in the former one actually probes the macroscopic screening currents which encounter a large number of defects, whereas the latter induces small (microscopic) current loops which see a relatively smaller cross section of defects in the films. This could be the possible reason for the absence of PE in the magnetization studies in these films.

It is important to note that the PE at dc or low frequencies is observed at high fields or high currents; on the other hand, the peak in R_s at microwave frequencies is observed at low fields as well as low currents, much below the dc critical currents. Obviously therefore, ω_p is central in these observations. ω_p is determined by κ_p and η , which are in turn dependent on the nature and distribution of pinning centers.¹⁰ YBCO thin films grown by PLD are known to have various types of defects such as uncorrelated defects (point defects, oxygen vacancies, or their clusters, secondary phase precipitates) or correlated defects such as twin boundaries which arise from twinned substrates. Therefore, it is logical to assume that the characteristic depinning frequency ω_p of the film is an effective sum of the depinning frequencies (ω_{p1} , ω_{p2} , ...) associated with different defects. In this scenario, the defects with lower ω_p (say ω_{p1} determined by defect density and κ_p) will show a PE at lower frequency (ω_1) followed by another peak at a higher frequency (ω_2) due to other defects with higher ω_p (ω_{p2}). Further, it should also

be possible to observe more than one peak at a given measurement frequency if there exist sets of defects with different κ_p values. The observation of secondary peaks in low frequency J_c - T plots and their possible origin has been widely studied in the literature.¹⁹

The above picture explains qualitatively, our observations. First, the peak at T_{p1} , at 4.88 GHz (Fig. 1) can be associated with pinning centers such as point defects and oxygen vacancy clusters (κ_{p1}). As the frequency is increased to 9.55 GHz, other defects such as twin boundaries with higher κ_p (and hence, higher ω_p values) become active giving rise to an additional peak (T_{p2}) shown in Fig. 2. The angular dependence of this peak (as shown in the top inset of Fig. 2) indicates that this additional peak at 9.55 GHz could be due to twin boundaries. Recent magneto-optical imaging and magnetization measurements have also pointed out that the twin boundaries are easy paths for vortex pinning.^{20,21} Further, the peak at T_{p1} shifts to lower temperature at 9.55 GHz. This can be explained by the temperature dependence of ω_p (Ref. 10) which increases with decreasing temperature. In other words, the peak due to a given set of defect structures (point defects or oxygen vacancies in the present case) with associated ω_p at a given temperature should shift to lower temperature as the measurement frequency is increased.

The bottom inset in Fig. 2 is a plot of $1/R_s$ (normalized) vs T at a field value of 0.4 T. To understand the significance of this plot let us go back to our earlier correlation of J_c with ω_p , and hence, R_s .¹⁴ It is seen that the variation of $1/R_s$ (normalized) is similar to that of J_c and shows a peak before T_c (H_{c2}). Ion irradiation and creation of correlated defect centers as CD's are well known to strongly pin the flux lines in such defect sites. Liberating a vortex from CD's requires considerable amount of energy causing an increase in J_c . This is reflected in an increase in $1/R_s$ (normalized) in our case.

In the absence of a suitable theory we have earlier proposed a model variation of depinning frequency ω_p with T/T_c , which shows a minimum followed by a peak at T_p .¹⁴ Thus, at a frequency 4.88 GHz (where $\omega < \omega_p^{\text{dip}}$ or ω_1 in curve "a" of Fig. 3), the peak observed is less pronounced as compared to that at 9.55 GHz (where $\omega_p^{\text{peak}} > \omega_2 > \omega_p^{\text{dip}}$, curve "a" in Fig. 3). Artificially introduced defects such as columnar defects lying in the vicinity of the existing defects enhance their pinning strength κ_p and prevent a flux line to be depinned at 4.88 GHz from such sites. In other words, ω_p of the YBCO film is increased above 4.88 GHz which is depicted in the upward shift of the model plot (curve "b" of Fig. 3). However, the irradiation induced enhancement in ω_p is insufficient to keep the vortices pinned at 9.55 GHz; hence there is no suppression of the peak at T_{p1} after irradiation.

The peak near T_c (at T_{p1}) can be associated with a transformation of the FLL from a pinned solid to a depinned liquid in the depinning frequency domain similar to the order-disorder transformation of the FLL associated with the PE in critical currents in dc or low frequencies as the temperature or field is increased. Based on the temperature variation of R_s (at 9.55 GHz), tentative vortex phase diagrams

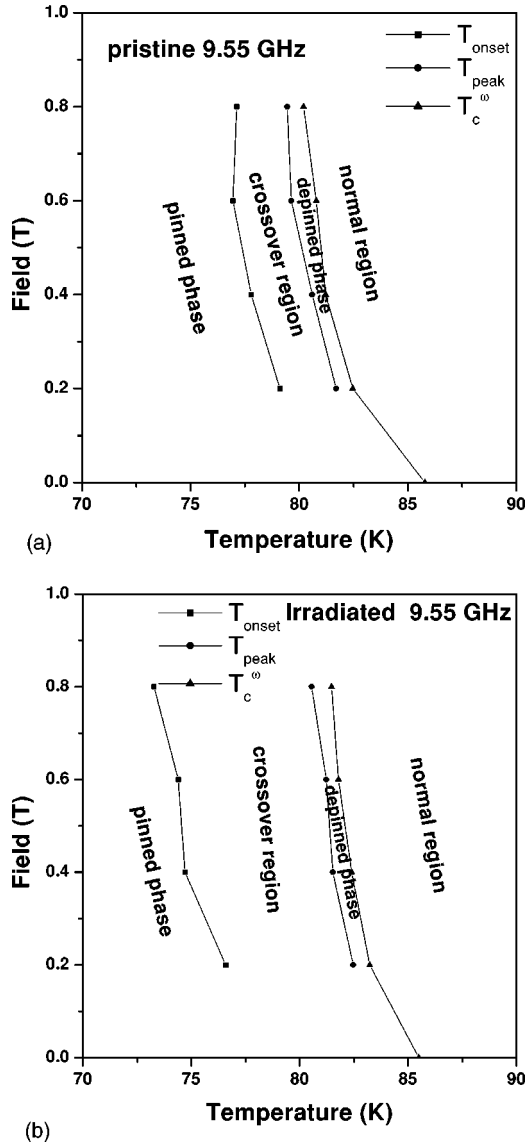


FIG. 4. Phase diagrams: (a) At 9.55 GHz, pristine sample. (b) At 9.55 GHz, irradiated sample.

have been constructed and shown in Fig. 4 for the pristine and irradiated samples. The onset of such a transformation of the FLL indicated by T_{onset} (onset of peak in R_s) corresponds to a minimum in $\omega_p(\omega_p^{\text{dip}})$. The process of depinning is complete at the peak in $\omega_p(\omega_p^{\text{peak}})$ which corresponds to a minimum of R_s at T_{p1} . Hence, the phase diagram shown comprises a pinned vortex state, which crosses over to a fully depinned state via a partially pinned vortex state as the temperature or field is increased. The crossover region broadens out over a greater temperature range in the case of the irradiated sample. The subsequent transformation to the normal

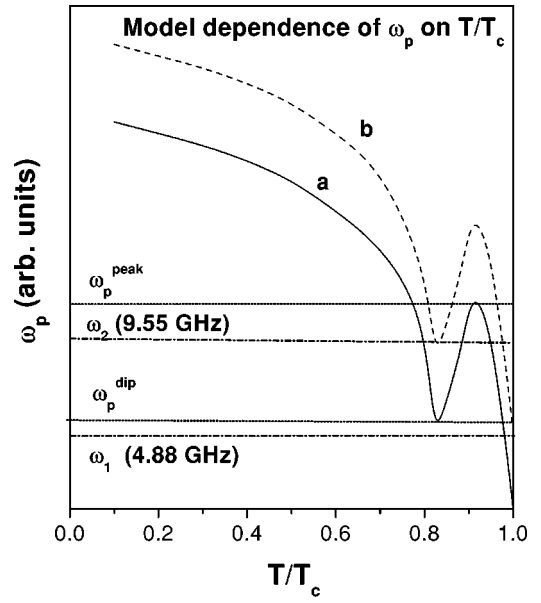


FIG. 3. Model dependence of ω_p on T/T_c for (a) pristine sample and (b) the sample irradiated with 200 MeV Ag ions at a fluence of 4×10^{10} ions/cm².

phase is indicated by T_c^ω (T_c^ω is defined by the criterion, $R_s \sim 10$ m Ω). This indicates that irradiation introduces disorder in the system which modifies the dynamics of the vortex lattice in a major way.

IV. CONCLUSION

In summary, we have studied the vortex dynamics at microwave frequencies (4.88 and 9.55 GHz) in YBCO thin films for $H//c$ before and after irradiation with 200 MeV Ag ions at a fluence of 4×10^{10} ions/cm². We have shown that the peak in R_s at such frequencies critically depends on the nature and concentration of defects. A suppression of the peak at 4.88 GHz is observed after irradiation due to enhanced pinning by the columnar defects which shifts the ω_p vs T/T_c model plot (proposed in our earlier work) to higher ω_p values. From the angular-dependence measurements of R_s with magnetic field, the peak at T_{p2} observed at 9.55 GHz, can be related to the twin boundaries. From the phase diagrams, based on the temperature variation of R_s at 9.55 GHz, we see that irradiation induced disorder broadens the crossover region between the pinned and the depinned phase.

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